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An Introduction to Power and Energy

This article provides a brief overview of some of the most common sources of power and energy. It certainly is not comprehensive, but it does provide a solid background for many of the technical areas of power and energy presented in the other articles in this publication.

INTRODUCTION

Power and energy enable the use of the most advanced weapons, electronics, vehicles, and facilities available to the warfighter. Without consistent and reliable power and energy sources, the ability of the military to carry out their mission would be severely compromised. There are many ongoing efforts to develop new and enhance existing energy and power supply technologies, while reducing the consumption of energy. This article introduces a variety of sources of energy and covers some of the more common devices used to convert energy from one form to another.

Definitions

Basically defined, *energy* is a system's ability to perform work, and *power* is the rate at which energy is transferred to perform work. There are many forms of energy but all forms can be placed into one of two categories: kinetic and potential. Kinetic energy is simply the energy of motion. Potential energy is the energy stored by an object or system due to its position or state. Forms of kinetic energy include electrical, radiant, sound, motion and thermal energy. Forms of potential energy include chemical, gravitational, nuclear, and stored mechanical energy. A *fuel* is a substance that has stored energy which can be released deliberately to provide useful work or provide heat.

There are many sources of energy which are used to perform work on a system of any scale. For instance, on a molecular scale thermal energy can be used to form or destroy bonds between atoms and molecules. On a macroscopic scale, chemical energy stored in an energetic material, for example, can be used to propel a rocket away from the Earth's gravitational pull. Aside from the natural energy sources that sustain living organisms, various energy sources are harvested and used to power the function of artificial devices and processes.

ENERGY SOURCES AND FUELS

Energy behaves according to the First Law of Thermodynamics, also known as the law of conservation of energy, which can be formalized as:

> *Although energy assumes many forms, the total quantity of energy is constant, and when energy disappears in one form it appears simultaneously in other forms.*[1]

From this law it is clear that energy cannot be created, but rather converted from one form to another. Thus energy must be harvested from various sources.

Energy sources can be categorized in a variety of ways. Perhaps the most meaningful approach is to separate them into nonrenewable and renewable categories. *Nonrenewable energy* sources cannot be regenerated or replaced within a timescale that is sufficient to sustain their consumption. Thus, these energy sources will eventually become exhausted. Conversely, *renewable energy* sources can be replenished by natural processes at a rate that exceeds their consumption.

NONRENEWABLE ENERGY SOURCES

There are many fuel products that can be derived from nonrenewable energy sources. Even though by definition they are finite in quantity, nonrenewable energy sources are the most commonly used in part because they have very high energy densities that can be readily converted into useful work. Most common nonrenewable energy sources are derived from fossil fuels, however, radioactive materials provide nonrenewable nuclear energy.

Fossil Energy Sources and Fuels

Fossil fuels are derived from carbonaceous or hydrocarbon solids, liquids, and gases that have been formed from the decay of organisms contained within the Earth's crust that were exposed to heat and pressure over time. The most common fossil energy sources are petroleum, coal and natural gas.

Petroleum

Crude oil or petroleum is a natural, but nonrenewable fossil fuel primarily composed of a mixture hydrocarbons, including alkanes, cycloalkanes, and aromatic compounds. Nitrogen, sulfur, and oxygen are also present in the hydrocarbon compounds, and iron, nickel, copper and vanadium are also present in small amounts of the petroleum.

Petroleum is refined by fractional distillation process to convert the crude liquid to refinery gas, gasoline, kerosene, and diesel fuel. The liquids and solids remaining after distillation are lubricating oils, paraffin wax, asphalt and bitumen. The largest petroleum reserves are located in Saudi Arabia, Canada, Iran, Iraq, Kuwait, United Arab Emirates, Venezuela, Russia, Libya, Nigeria, United States, China, Qatar, and Mexico.

As the largest consumer of energy in the US, the DoD is also the largest consumer of petroleum products by using approximately 360 thousand barrels per day in 2007. This consumption cost approximately $11.5B. [2,3]

Gasoline

A common fuel derived from petroleum is a composition of aliphatic* compounds and enhanced with isooctane or benzene and toluene. Gasoline is a refined product of petroleum that contains a mixture of hydrocarbons having between 4 and 10

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14. ABSTRACT
This article provides a brief overview of some of the most common sources of power and energy. It certainly is not comprehensive, but it does provide a short background for many of the technical areas of power and energy presented in the other articles in this publication. Power and energy enable the use of the most advanced weapons, electronics, vehicles, and facilities available to the warfighter. Without consistent and reliable power and energy sources, the ability of the military to carry out their mission would be severely compromised. There are many ongoing efforts to develop new and enhance existing energy and power supply technologies, while reducing the consumption of energy. This article introduces a variety of sources of energy and covers some of the more common devices used to convert energy from one form to another for the purpose of providing power.

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Table 1. Sample Composition of Gasoline.[4]

Component	Percent Composition by Volume
C_4 – C_8 Straight-Chain Paraffins†	15%
C_4 – C_{10} Branched Paraffins	25-40%
Naphthenes‡	10%
Aromatics§	<25%
Olefins**	10%

Table 2. Energy Density of Aviation Fuels.[5]

Aviation Fuel	Volumetric Energy Density (MJ/m^3)
Jet A	35,000
Jet A-1	35,000
JP-8	35,000
JP-9	39,573
JP-10	39,434

carbon atoms and other additives. The composition can vary significantly depending on environmental regulations which determine the blending requirements.

Like many fuels, gasoline releases its energy during combustion. For combustion to occur effectively, however, gasoline must readily mix with oxygen or air. Therefore an important property is its vapor pressure, which is dependent on temperature. Adjusting the butane (C_4H_{10}) content of the fuel can help control the vapor pressure. Under sufficient compression, gasoline can spontaneously combust without supplying a spark. This premature ignition or pre-detonation can damage internal combustion engines, however. The octane rating of gasoline refers to the mixture's propensity or resistance to pre-detonation. A higher octane rating indicates a greater resistance to pre-detonation.

Diesel

Diesel is another refinery product of petroleum. Diesel contains longer-chain hydrocarbons than gasoline, typically with 10 to 15 carbon atoms, and thus has a higher density. Diesel also has a higher energy density than gasoline.

Aviation Fuel

Aviation fuel is refined from petroleum and specially formulated to operate in aircraft or turbine engines on ground vehicles. Similar to gasoline and diesel, aviation fuels contain paraffins, olefins, naphthene, and aromatic hydrocarbons, as well as additives that impart chemical stability and other properties to the formulation. Important properties of aviation fuels include flash point, freezing point, energy density, density, stability (e.g., thermal, storage), volatility, lubricity, fluidity (e.g., viscosity), resistance to microbial growth, and inhibition of corrosion.[5] Aviation fuels are primarily based on kerosene, which is a mixture of hydrocarbons with 12 to 15 carbon atoms.

Jet A. The formulation known as Jet A is the standard commercial aviation fuel in the US. It is a kerosene-based fuel with a flash point†† of 38°C and a freezing point of -40°C.

Jet A-1. Jet A-1 aviation fuel is used by commercial airlines outside the US. Like Jet A fuel, Jet A-1 has a flash point 38°C, but it has a freezing point of -47°C.[5]

JP-5. Jet Propellant-5 (JP-5) is a kerosene-based jet fuel formulated to meet military specifications for certain properties. For instance, JP-5 has a higher flash point (minimum of 60°C) than commercial aviation fuels and a maximum freezing point of -46°C. The US Navy stores JP-5 aboard its aircraft carriers because of its relatively high flash point and low volatility, which makes it safer and less susceptible to ignition.

JP-8. JP-8 is a common kerosene-based military aviation fuel with a minimum flash point of 38°C and a maximum freezing point of -47°C.

JP-8+100. Based on JP-8, JP-8+100 has an additive package (consisting of a detergent, dispersant, metal deactivators and antioxidant) used to improve its thermal stability by 100°F.

JP-9 and JP-10. JP-9 and JP-10 are specialty fuels primarily for missile applications and are composed almost entirely of high-density naphthenes.[5] The JP-9 formulation is a blend of methylcyclohexane, perhydronorbornadiene dimer, and exotetrahydrodiclyclopentadiene.[5] The JP-10 formulation consists of a single hydrocarbon, exotetrahydrodiclyclopentadiene. The energy density for several aviation fuels is presented in Table 2.

Coal

Coal is an abundant, solid, nonrenewable fossil fuel that has been used as an energy resource for thousands of years. Explorers discovered coal in US in 1673, but commercial production (i.e., mining) did not begin until 1748 in Virginia.[6] There are several different types of coal, including lignite, sub-bituminous, bituminous, anthracite, and graphite.

Coal is commonly used as a fuel source for combustion to convert its stored energy to heat. This can be used as a simple heat source or to generate steam to drive a turbine and generate electricity.

Even though coal is found throughout the world, the US has the largest known coal resource. The coal reserves are spread across large areas of the country and it is mined in 27 states. The Department of Energy (DOE) estimates that 92% of the coal consumed in the US is used to generate electricity. The electricity generated from coal makes up approximately half of the electricity produced in the US. As of 2007, the US Army had seven

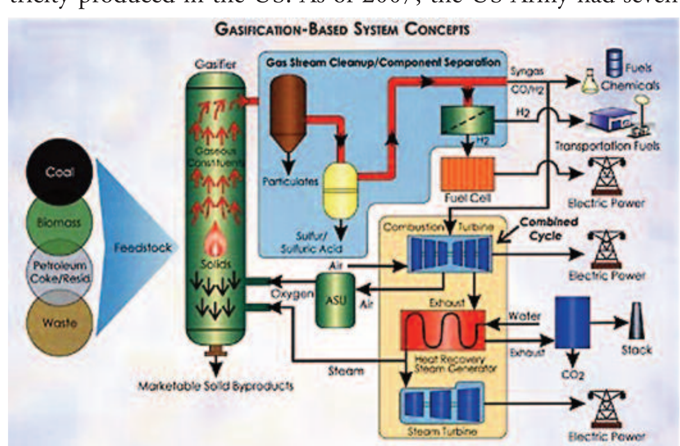

Figure 1. Coal Gasification Process.[8]

coal-fired power plants. These produced more than 7.6 million BTUs (British Thermal Units) of energy.[7]

Coal Gasification. Coal can be converted into other types of energy sources or fuels, such as synthetic fuel (see *Synthetic Fuel* below) and hydrogen, through a process that decomposes the solid into its base constituents in the presence of steam and oxygen under high temperature and pressure conditions (see Figure 1). The products of this gasification process are carbon monoxide, hydrogen and other gaseous compounds. During the process contaminants are separated and removed.

Coal Liquification (Coal-To-Liquid). Coal can be converted directly to a liquid or indirectly to a liquid through the gasification and Fischer-Tropsch processes.

Natural Gas

Natural gas is a naturally occurring, nonrenewable fossil fuel, and unrefined it is a mixture of gaseous hydrocarbons, primarily methane (CH_4). Natural gas can be collected from a variety of sources, including landfills and the anaerobic digestion of organic waste (i.e., decaying of biomass), but most commonly it is collected from crude oil and natural gas fields.

Natural gas is an abundant natural resource, especially in the US, and is therefore relatively affordable. Most natural gas deposits are a few thousand feet beneath the Earth's surface, but some can be more than 15,000 feet below the surface. Natural gas associated with crude oil can exist as a dissolved gas or free gas. Nonassociated natural gas exists in deposits absent of crude oil.

Methane hydrates are being studied as a possible alternative source of natural gas. Clathrate compounds are formed when water molecules bond in such a way as to encapsulate another molecule. A methane clathrates, also known as a methane hydrate, is an example of such a unique molecular structure that surrounds a methane molecule. These compounds have been found embedded in the ocean floor, sedimentary layers and in permafrost.

Properties. Natural gas is a colorless, odorless , non-poisonous, flammable substance. An odorant, typically butanethiol (also known as t-butyl mercaptan) or tetrahydrothiophene, is added in small amounts to aid the detection of natural gas leaks.

Table 3. **Typical Composition of Unrefined Natural Gas.[9]**

Methane	CH_4	70-90%
Ethane	C_2H_6	
Propane	C_3H_8	0-20%
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulfide	H_2S	0-5%
Rare gases	He, Ne, Xe	trace

Table 4. **Potential emissions reductions through the combustion of natural gas instead of gasoline.[14]**

Carbon monoxide (CO)	90-97%
Carbon dioxide (CO_2)	25%
Nitrogen oxides	35-60%
Hydrocarbons (non-methane)	50-75%

Prior to refining, the typical composition of natural gas is 70-90% methane, by volume, but also includes ethane, propane, butane and other alkanes (see Table 3). Other contents found in this fossil fuel include nitrogen, helium, carbon dioxide, water vapor and hydrogen sulfide. After refinement, commercial grade natural gas is almost entirely composed of methane.

Methane is in gaseous form at room temperature, condenses at -164°C, and freezes at -183°C. The density of methane is 0.67 kg/m3 at standard temperature and pressure (STP) compared to the density of dry air: 1.29 kg/m^3.[10,11] Methane is slightly soluble in water, for instance 3.5 ml of methane dissolves in 100 ml of water at 17°C. It is also soluble in alcohol, ether, and other organic solvents.[12]

Methane reacts with oxygen to produce carbon dioxide, water vapor and heat according to the following equation

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l) + 890\ kJ$$

When fuel is mixed with air combustion occurs when natural gas concentration is between 5-15%.[12] The autoignition temperature of methane is 650°C.[12]

The products after combustion of natural gas are primarily carbon dioxide and water, whereas other fuels have a notable amount of additional byproducts. Therefore, natural gas results in a cleaner combustion than gasoline or diesel. Potential emissions reductions by using natural gas instead of gasoline have been estimated and are shown in Table 4.

In addition to reductions in these compounds, combustion of natural gas results in a reduction in carcinogenic pollutants and particulate matter compared to combustion of gasoline. Natural gas is considered to have an octane rating higher than gasoline.

Processing. Natural gas harvested from petroleum wells and other sources must be processed and refined to remove many of the unnecessary components and impurities to produce a commercial grade fuel. Alkanes other than methane are removed and collected for other uses.

Particulates, such as sand, are removed by scrubbers. In the case of natural gas dissolved in crude oil, it must be separated using a gravity separator, for example. Some water can be condensed out of the natural gas during refining, but dissolved water must be removed through absorption or adsorption.

Organic contents other than methane, such as ethane, propane, and butane are also extracted and subsequently separated as byproducts for other uses. Absorption is the method commonly used to extract the heavier organic compounds from the unrefined natural gas, while cryogenic expansion is used to extract compounds such as ethane which is close in

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molecular weight to methane. Separation of the hydrocarbons is then accomplished by fractionation methods.

Hydrogen sulfide is removed from unrefined natural gas by an absorption process. Amine compounds can be used to absorb hydrogen sulfide thereby extracting it from the natural gas stream. Elemental sulfur can subsequently be recovered for use in other applications.

Applications. As a combustible substance that can provide thermal energy, natural gas is commonly used for heating and cooking. However, there are several other applications of natural gas, such as fuel for vehicles and as a source of hydrogen for hydrogen production. In 2007, 29% of the nation's natural gas was used in industrial applications, 24% was used for residential heat and power, and 0.1% was used for transportation applications.[13]

Natural gas vehicles (NGVs) use compressed natural gas (CNG) or liquid natural gas (LNG). This is because if natural gas is used in its unpressurized, gaseous form a large volume is needed to power a vehicle for an acceptable distance. Even with CNG or LNG, NGVs have a more limited range than vehicles powered on conventional fuels. However, the power output of engines fueled by natural gas is comparable to those powered by conventional fuels. Natural gas vehicles can be powered by dedicated natural gas engines or bi-fuel engines which can run on either natural gas or a conventional fuel.[13]

Distribution. Small diameter pipelines are typically used to transport unrefined natural gas from the collection point to the processing plant or storage facility. The US has a network of interstate and intrastate pipelines which are used to transport natural gas from processing plants to the point of final distribution and consumption. Interstate pipelines are high pressure lines and are kept pressurized by compressing stations. Metering stations are also placed along the pipeline to monitor the natural gas in the line.

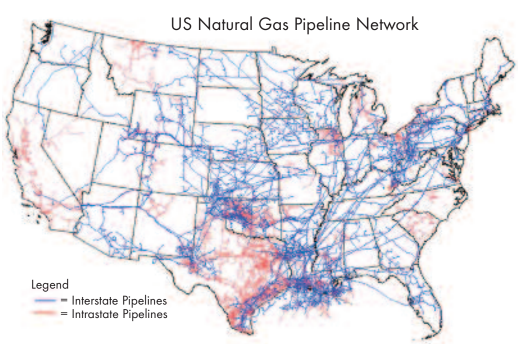

Figure 2. US natural gas pipeline network.[15]

Storage. Depleted gas reservoirs are used to store large volumes of natural gas underground. When a natural gas well becomes exhausted it can be used to store refined natural gas. In a similar way, underground salt caverns can be used to store natural gas. Natural water aquifers also can be reconditioned and used to store natural gas underground.

Synthetic Fuel

Synthetic fuel is technically defined as "a fuel that is artificially formulated and manufactured."[16] However, synthetic fuels are commonly described as liquid fuels derived from "coal, natural gas, or other solid carbon-containing feedstocks."[17] Synthetic fuels can also be extracted from oil shale and tar sands.[17]

History. Synthetic fuels were first made possible when the Fischer-Tropsch process was developed in the 1920s by Franz Fischer and Hans Tropsch. This process formulates hydrocarbon fuels from carbon monoxide (CO) and hydrogen gas (H_2), which allows carbon based products to be transformed into useful hydrocarbon fuel and lubricant products. The hydrocarbon product is formed when the reactants are passed through a catalyst under heat.

Advantages. During combustion synthetic fuels produce less carbon dioxide, particulate matter and sulfur compared to petroleum products refined from crude oil. This is because synthetic fuels are fabricated from "cleaner" reactants than crude oil-based petroleum products that are typically contaminated with nitrogen, sulfur, iron, nickel, copper, and vanadium. Good low temperature properties and excellent thermal stability are also noted as advantages of synthetic fuels.[16] Raw materials that are used as feedstocks for formulating synthetic fuels (e.g., coal and natural gas) are naturally occurring in US territory. Synthetic fuels that can be produced include gasoline, diesel, kerosene and various formulations of aviation/jet fuel. Synthetic fuels can also be used in existing engines and can be distributed using the existing infrastructure.

Disadvantages. Although the combustion of synthetic fuels produces less carbon dioxide than the combustion of fuels from petroleum products, the production of synthetic fuels results in high carbon emissions. The sulfur from petroleum-based fuels helps in the lubrication of moving engine parts. In addition, aromatic hydrocarbons, which are present in petroleum-based fuels, cause elastomeric seals to swell and therefore provide enhanced sealing capability. Finally, the mining of coal, which is one of the primary raw materials for synthetic fuels, is hazardous and can be environmentally damaging.

Department of Defense Use of Synthetic Fuels. The Air Force has been testing formulations of jet fuel that blends conventional jet fuel with the synthetic formulation. The Air Force has tested the synthetic fuel blend on several aircraft including the C-17 Globemaster III,[18] the B-1B Lancer,[19] the B-52 Stratofortress,[20] the F-15E Strike Eagle,[21] and the F-22 Raptor[22]. On March 19, 2008, the B-1B became the first Air Force aircraft to fly at supersonic speeds using the synthetic jet fuel blend. On August 19, 2008, the F-15E became the first Air Force fighter aircraft to fly using the synthetic fuel blend. The Army has been testing synthetic fuels for their vehicles as well. Performance and durability were evaluated with a synthetic fuel in the Caterpillar C7 engine.[23]

Nuclear Energy

Nuclear energy is the energy contained within the nucleus of an atom, specifically the energy that binds the nucleus together. Some of this energy can be released when nucleons (i.e., protons or neutrons) are split apart (fission) or fused together (fusion). Fission and fusion occur naturally. Radioactive materials are inherently unstable and decay over time by releasing packets of matter and/or energy. In some cases, the unstable nucleus of a radioactive material fissions and releases nucleons to achieve a more stable material. Fusion occurs naturally, for example, under the immense pressure and temperature of stars, such as the sun.

Although fusion reactions convert mass into enormous amounts of energy, only fission is currently a viable source of power for conventional applications.

Nuclear power is based on an abundant resource of energy, and generates electricity essentially by extracting energy from the atomic nucleus. Heat from the fission of atomic nuclei is used to create steam, which powers a turbine and ultimately converts the energy into electricity. However, since fission reactions in most stable matter do not readily occur (i.e., consume more energy than they produce), nuclear reactors use radioactive uranium or plutonium as fuel.

Nuclear power is known to produce electricity without the carbon emissions and other green house gas emissions associated with the use of petroleum and coal. However, it is the inherent danger associated with nuclear reactions as well as the challenge of handling and disposing of nuclear waste that has kept nuclear power from becoming the primary energy resource in the US.

At the end of 2007, there were 104 operational commercial nuclear reactors in the US.[24] However, nuclear power is not only limited to stationary facilities. The US Navy has ten aircraft carriers and more than sixty submarines powered by nuclear reactors.[25]

Nuclear Fission

Nuclear power is derived from nuclear fission reactions, in which a radioactive material is bombarded with matter to induce fission of the nuclei. As the nuclei fission, matter and energy are released. The ejected matter bombards other nuclei causing a chain reaction to occur. The energy is captured to be converted to useful work to ultimately generate electricity (see *Nuclear Power*).

Radioactive materials for conventional nuclear power are relatively rare and are considered nonrenewable. Uranium-235 (U-235) is a commonly used nuclear fuel and is extracted from uranium ore. The refining process involves the extraction of uranium oxide (U_3O_8) from the ore. Chemical processing refines the uranium oxide to uranium dioxide (UO_2) or metallic uranium. The enrichment of uranium refers to increasing the ratio of U-235 to uranium-238, a less radioactive isotope.

RENEWABLE ENERGY SOURCES

Renewable energy sources are drawing more attention globally because of their potential to reduce the reliance on nonrenewable sources including those that may be harmful to the environment. Natural resources that can be replenished on a time scale which can sustain their consumption are generally considered renewable. These energy sources typically include geothermal, wind, solar, biomass, and hydro. Each of these is discussed in some detail in the following sections.

Geothermal Energy

Geothermal energy is a renewable and abundant resource. The word geothermal refers to the thermal energy contained below the surface of the Earth. The center of the Earth is believed to have a temperature more than 11,000°F, which is approximately the temperature at the surface of the sun.[26,27] The Earth's thermal energy is derived from several natural processes.

A portion of the Earth's thermal energy remains from when the planet was originally formed by the condensation of hot gases and particles under gravitational forces. Additionally, as denser components were drawn to the center during the Earth's formation, the less dense materials were displaced toward the surface. This differentiation process involved friction, in which heat was generated, and some of the heat from this process was also retained. Moreover, latent heat is released from the core as it cools and expands in volume. Most of the Earth's heat, however, is derived from the isotopes of radioactive elements, such as plutonium, uranium and thorium, which are contained in the Earth's mantle and crust (see Figure 3). These radioactive materials release energy as they decay to become stable elements.[26]

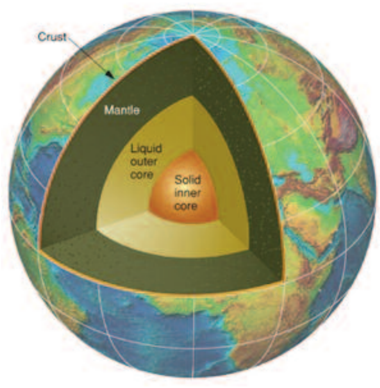

Figure 3. **Most of the Earth's heat is generated in the mantle and crust. (Graphic courtesy Lawrence Livermore National Laboratory)**

The thermal energy from the Earth is dispersed across the surface relatively uniformly, and temperatures increase as depth below the surface increases. However, there are geographical features which permit areas where higher subsurface temperatures can be more readily accessed. For instance, subsurface temperatures are higher near tectonic plate boundaries. Iceland has an advantage over other nations because the country is located where two tectonic plates meet. Other geographical features include volcanoes, hot springs and geysers. The Earth's thermal energy is a valuable resource, but the challenge is in how to capture and use it.

Direct Use of Geothermal Energy

Geothermal energy heats some natural bodies of water, such as underground reservoirs, which thus are considered *hydrothermal* sources of energy. Hot springs are natural springs that absorb geothermal energy. Hot water from these resources can be pumped directly into facilities to provide heat. Cities in Iceland utilize this inexpensive form of energy to heat entire districts.

Geothermal Electric Power

Electric power can be generated from hydrothermal resources. Hot water or steam is collected from hydrothermal resources within the earth. In some locations these resources are readily accessible, but other locations require drilling geothermal wells that are one to two miles deep. Geothermal steam can be used to

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drive turbines, thereby generating electricity. The majority of geothermal plants draw pressurized hot water from deep wells, convert it to steam, and use the steam to drive turbines, thereby generating electricity. These types of plants are geothermal flash steam plants. Other types of geothermal plants transfer heat from hydrothermal resources to another substance via heat exchange. US geothermal power plants are located in California, Nevada, Hawaii, and Utah.

Active and Passive Geothermal Systems

The temperature of the Earth's crust near the surface is relatively uniform regardless of geographic location or climate above the surface. The temperature generally ranges between 50-60°F. At depths of 15 feet temperatures fluctuations are 10°F or less.[28] These nearly constant temperatures can be used effectively as a natural heat exchanger to heat and cool facilities.

Active. In *active geothermal systems*, heat pumps circulate a fluid, usually water or a refrigerant, between a piping system buried in the earth and a building. The piping system exchanges heat to and from the earth depending on whether it is performing the function of cooling or heating. Basically, during warm seasons heat is absorbed from the building and dissipated into the earth for cooling, and during cool seasons heat is absorbed from the earth by the piping system fluid and is delivered to the building. These geothermal systems when used in conjunction with a well-insulated facility can serve as a highly efficient, low-cost method for providing heating and cooling.

Passive. The simplest use of geothermal energy is through passive geothermal systems. Similar to active systems a series of pipes containing a refrigerant, sometimes water, exchanges heat between the facility and the ground. The absence of a pump renders this a *passive geothermal system*. These systems have vertical pipes running from the foundation to several feet into the ground. Heat from the ground is drawn up into the building.

Advantages and Disadvantages

There are numerous advantages and few drawbacks of geothermal heating and cooling systems. In addition to geothermal energy being a renewable resource, advantages of systems that use it include low operating cost, low maintenance, and low or no emissions. The Environmental Protection Agency considers geothermal systems the "most energy-efficient, environmentally clean, and cost-effective systems for temperature control." The main drawback is the relatively high capital cost required to install the piping system, which may require borehole drilling. However, this cost can be recovered in a relatively short period of time through savings in conventional energy costs. In addition, supplemental heating and cooling systems may be required for facilities that are not well insulated or installations that are located in extreme climates.

Wind Energy

Wind power is a rapidly growing source of energy production in the US. Wind is an abundant, renewable, ultra-clean source of energy that can be harvested by wind turbines and converted to electricity. Although the power output of a single windmill is relatively small, wind farms can produce a substantial amount of energy.

The Earth is unevenly heated by the sun, which causes temperature differences and pressure gradients. Air flows as a result of pressure gradients and other forces. The kinetic energy of wind can be harnessed to drive mechanical devices which convert it into a useful energy to generate electricity.

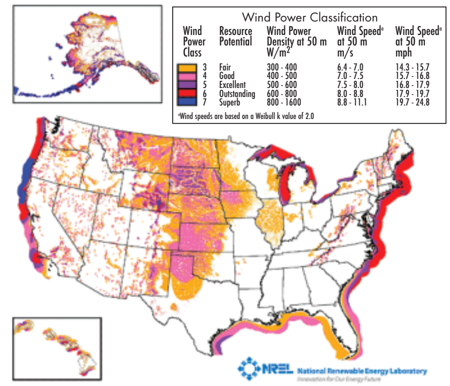

Figure 4. Wind distribution in the US.[29]

The energy of the wind has been harnessed by humans for thousands of years. Wind was used for marine vessel propulsion by the ancient Egyptians, and wind mills were built by the ancient Chinese to pump water and the ancient Persians to grind grains. Denmark is known for their use of wind mills to generate electricity, which began in the late 19th Century.

Since wind is naturally occurring and generated primarily because of the sun's energy it is a renewable resource. Wind energy is ultra clean because there is no combustion involved in the generation of electricity. Moreover, wind is an inexpensive and abundant domestic resource. It can be cost competitive with other conventional electricity generating methods. Wind farms and individual wind turbines can be built almost anywhere, including offshore.

One of the primary challenges with wind power is the irregular nature of wind, which results in the inconsistent generation of electricity. Energy storage devices can be used to enable a more consistent supply of electricity. Depending on the location and energy requirement, another challenge is the size and number of wind turbines needed to generate sufficient electricity.

Wind power density in the US ranges varies significantly across the nation (see Figure 4). The highest wind power density is typically found offshore, and at elevations of 50 m it can be in the range of 600 – 1600 W/m^2.[29]

Bioenergy

Bioenergy is renewable energy derived from biomass. Biomass is organic or biological matter that can be used for or converted to fuel. This generally includes matter from plants and animals, but excludes the organic matter that has been converted fossil fuel. Biomass, such as wood, has been used for millennia to produce heat, and other biomass, such as sugar cane, can be processed to produce ethanol for use as a biofuel.

Biofuels are predominantly synthetic fuels but have an important distinction due to the raw materials used to manufacture them. The feedstocks originate from biomass which includes agricultural crops (e.g., corn), wood, plants, grasses, agricultural waste, and other waste products.[30,31] Biomass is defined as "any organic matter that is available on a renewable or recurring basis."[31]

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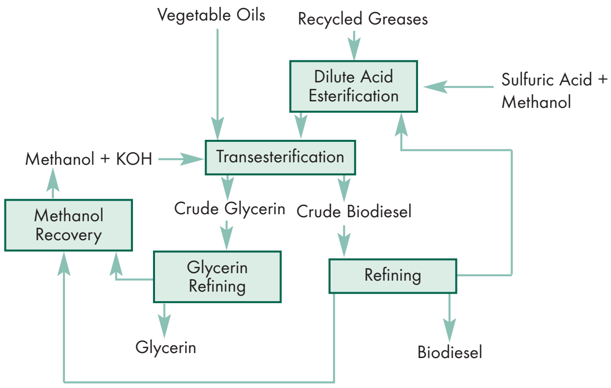

Figure 5. Example of a biodiesel production process.[32]

Ethanol and Other Alcohols

Sugar, which is extracted from plants and other biomass, can be decomposed through microbial fermentation to produce ethanol and carbon dioxide.[32] The sugar is extracted by milling, crushing, soaking, and chemically treating the feedstock. The ethanol produced by fermentation is distilled to purify and separate it from water.[33] Methanol, propanol, and butanol can be produced using a similar process.

Biodiesel

Biodiesel is primarily derived from soybean oil in the US, but vegetable oil, rapeseed oil, sunflower oil, palm oil, animal fats and algae can be processed to produce biodiesel. This is accomplished through transesterification of the feedstock, which produces biodiesel fuel as well as crude glycerin (see Figure 5). Crude glycerin, as a byproduct of the transesterification process, can be re-processed and used for a variety of other products. Mono-alkyl esters and long-chain fatty acids are the major constituents of biodiesel, but it can be blended with diesel derived from petroleum products. This synthetic blend has a lower sulfur content than conventional diesel, but unlike synthetic fuels the biodiesel composition has good lubricating qualities. Biodiesel also has a higher energy density than ethanol.

Biofuel Requirements for Use as Jet Fuel

Typical biofuels do not have an energy density sufficient to serve as a jet fuel. In order to be used as jet fuel, biofuels must be able to achieve the energy density levels of JP-8.[32] Even if the energy density meets this requirement, no engine modifications should have to be made in order to use a biofuel as jet fuel. Finally, jet-fuel grade biofuel must be able to be produced in quantities sufficient to meet demand, and must be transportable and stable enough for typical fuel storage.

Production of Jet Fuel from Algae

Algae can be cultivated to produce specific oils which can be processed into high energy density hydrocarbons. Micro-algae is of interest for jet fuel because it can be used to produce a higher ratio of fuel-grade oil quantity per land area than other biomass. For instance, micro-algae is capable of producing between 5,000 and 15,000 gallons of oil per acre per year, while rapeseed can only produce approximately 130 gallons of oil per acre per year.[32] Algae oils can be processed using the same hydroprocessing technologies currently used for refining conventional oils. This can produce a fuel similar to kerosene and the jet fuels traditionally derived from petroleum products.

Advantages

One advantage of biofuel is that it is renewable since the feedstocks are obtained through renewable resources. Biofuels are also potentially “carbon neutral”. The carbon dioxide (CO_2) that is consumed during growth of the feedstock materials compensates for the CO_2 that is produced when the biofuel is combusted.[34] However, the production of biofuels requires energy, which thus causes additional CO_2 emissions, and therefore it is not entirely “carbon neutral”.

Disadvantages

The primary disadvantage of biofuels is that they typically have a relatively low energy density compared to conventional fuels.[34] Ethanol also has a relatively low operating temperature.[34] Biodiesel freezes when temperatures near 0 °C and therefore limit its performance in cold weather climates.[32] Blending biodiesel with conventional diesel can alleviate this deficiency to a certain extent. Both biodiesel and ethanol have greater affinity for water than conventional petroleum products, which can have negative consequences including increased corrosion.

Solar Energy

The sun provides an abundant and renewable source of energy in the form of electromagnetic radiation. Some of the thermal energy, which is transferred from the sun to the Earth via radiation, enables other energy sources, such as wind and bioenergy. Solar energy can be used directly for heat, converted to electricity using the photoelectric effect, or by harnessing the thermal energy for driving steam turbines. More than 1.3 kW/m^2 of solar energy is incident on the Earth's atmosphere. While solar energy may be an abundant energy source, it varies significantly across regions (see Figure 6) and in many cases it also requires a significant amount of work to convert it into usable energy.

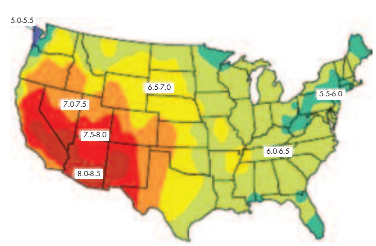

Figure 6. Map of average solar radiation received across a horizontal surface in the month of June (units are kWh/m^2/day).[35]

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Table 5. Physical and thermodynamic properties of hydrogen.[38,39,40,41]

Density†	0.08375 kg/m^3	0.005229 lb/ft^3
Specific volume†	11.94 m^3/kg	191.3 ft^3/lb
Viscosity†	8.813 x 10^{-5} g/cm-sec	5.922 x 10^{-6} lb/ft-sec
Specific heat (constant pressure)†	14.29 J/g-K	3.415 Btu/lb-°R
Specific heat (constant volume)†	10.16 J/g-K	2.428 Btu/lb-°R
Thermal conductivity†	0.1825 W/m-K	0.1054 Btu/ft-h-°R
Enthalpy†	3858.1 kJ/kg	1659.8 Btu/lb
Internal energy†‡	2648.3 kJ/kg	1139.3 Btu/lb
Autoignition temperature*	585ºC	1085°F
Flame temperature in air†	2045ºC	3713°F
Flammable range in air†	4.0 – 75.0 vol%	
Ignition energy in air	2 x 10^{-5} J	1.9 x 10^{-8} Btu
Higher heating value†	141.86 kJ/g	61,000 Btu/lb
Lower heating value†	119.93 kJ/g	51,500 Btu/lb

†At normal temperature and pressure = 20°C (68°F) and 1 atm

*The autoignition temperature depends on hydrogen concentration (minimum at stoichiometric combustion conditions), pressure, and even the surface characteristics of the vessel. Reported figures range from 932-1085°F.

‡Reference state: Internal Energy U=0 at 273.16 K for saturated liquid; Entropy S=0 at 273.16 K for saturated liquid.

Table 6. Volumetric and gravimetric energy density of hydrogen gas and liquid.[43]

	Volumetric Energy Density		Gravimetric Energy Density	
	MJ/m^3	Btu/ft^3	MJ/kg	Btu/lb
At 1 atm and 60°F (15°C)	10.1	270	120	51,700
At 3,000 psig and 60°F (15°C)	1,825	48,900	21,791	9,354,570
At 10,000 psig and 60°F (15°C)	4,500	121,000	53,730	23,147,300
Liquid	8,491	227,850	101,383	43,587,705

Hydroenergy

Hydro power can be defined as power derived from the potential and kinetic energy of water, and is therefore considered a renewable resource. Most commonly associated with the function of dams for generating hydroelectric power, hydro power is also generated by harnessing the energy of waves and tides.

Wave Power

Wave power is generated by harnessing the energy of surface waves or the pressure oscillations under the surface. This energy can be harvested using buoys, for example, that can convert the mechanical up and down motion into electricity. Wave power has had limited success, and is better suited to niche markets and regions proximal to wave energy rich resources, such as the Pacific Northwest.

Tidal Power

Tidal forces exerted on the Earth by the moon and, to a lesser extent, the sun cause the periodic rise and fall of ocean waters. This natural cycle is a source of energy that can be harvested and converted into useful power.

OTHER IMPORTANT SECONDARY ENERGY SOURCES‡‡

Hydrogen

Hydrogen in its elemental state, protium, is composed of a single proton and a single electron, while its isotopes deuterium and tritium contain an additional one and two neutrons, respectively. It is the most abundant element in the universe and is the lightest (i.e., smallest atomic mass). It is estimated that three quarters of the mass in the universe is composed of hydrogen atoms.[36] Hydrogen is very chemically reactive and readily combines with many other elements, particularly carbon and oxygen; on its own hydrogen is found in its relatively stable, diatomic gaseous form H2.[36]

Hydrogen gas, H_2, is highly flammable and when undergoing combustion (i.e., reaction with oxygen) it produces water and heat, as shown in the combustion equation:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) + 572 \text{ kJ}[37]$$

Since the only product is water and heat, hydrogen is a very clean burning fuel.

Hydrogen is not considered an energy source, but rather, an energy carrier like a spring, because it is not abundantly occurring on its own in nature and therefore must be produced from other compounds. Hydrogen can be produced by leveraging other renewable energy sources, such as wind, solar, and hydroelectric power, and therefore it can be supplied from a variety of geographical regions. Once produced, most commonly by steam methane reforming, hydrogen as a fuel can be used in internal combustion engines and fuel cells. Liquid hydrogen is also used as a propellant, and is well known for its use to launch the Space Shuttle. Selected physical and thermodynamic properties of hydrogen are given in Table 5.

Energy density is the amount of energy contained in matter per

unit mass or unit volume, and is often used to compare different types of fuels. The mass-based energy density of hydrogen is very high but the volume-based energy density is low compared to other fuels. One pound of H_2 has 44.4% of the energy contained in one gallon of gasoline.[42] The energy densities of hydrogen gas and liquid at several pressures are given in Table 6.

Hydrogen Production

Hydrogen as a resource is mostly contained in water (H_2O) and organic matter (i.e., hydrocarbons), and therefore must be extracted to be useable as a fuel. The following are some of the common processes used for hydrogen production.

Steam Methane Reforming. About 95% of the hydrogen produced today in the United States is made via steam-methane reforming, a process in which high-temperature steam (700°C-1000°C) is used to produce hydrogen from a methane source, such as natural gas which is mostly methane gas. In steam-methane reforming, methane reacts with steam under 3-25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide.[44]

Electrolysis. Electrolysis involves decomposing water into its base components of hydrogen and oxygen. This is accomplished by applying an electrical current through water via electrodes.

Gasification. Hydrogen can be produced by other organic feedstocks, such as coal and biomass. Using high temperature and pressure to gasify coal or biomass, the gasified organic product is then converted to synthetic gas, which is then reacted with steam under temperature and pressure to produce hydrogen. Syngas is primarily carbon monoxide and hydrogen (more than 85 percent by volume) and smaller quantities of carbon dioxide and methane. Syngas can be used as a fuel to generate electricity or steam, or as a basic chemical building block for a multitude of uses. When mixed with air, syngas can be used in gasoline or diesel engines with few modifications to the engine.[45]

Other Production Processes. Other processes used to produce hydrogen include renewable liquid reforming, nuclear high-temperature electrolysis, high-temperature thermochemical water splitting, and photobiological and photoelectrochemical processes.

Hydrogen Storage

In addition to its production, another technical challenge for hydrogen revolves around its storage. Even though hydrogen has a high energy density by mass, its energy density by volume is low. Therefore, storage of hydrogen fuel requires a sizable container that is also safe and reliable, since hydrogen is highly flammable.

Hydrogen can be stored in tanks as a compressed gas or cryogenic liquid or can be stored on the surface or within other materials, such as metal hydrides and carbon-based materials.

Electricity

Similar to hydrogen, electricity is a secondary energy source since it has to be generated (converted) from other energy sources. Electricity is the presence or movement of electric charge, and it is an extremely useful source of energy since it can be used to perform a variety of types of useful work.

POWER SOURCES (ENERGY CONVERSION)

There are myriad devices (natural and artificial) that can convert energy from one form to another. Since there are many, this section briefly discusses some of the more important (i.e., common) energy conversion devices.

INTERNAL COMBUSTION ENGINE

The internal combustion engine (ICE) is one of the most common and easily recognizable energy conversion systems used today. These engines are commonly divided into two groups: continuous-combustion and intermittent-combustion. Internal combustion engines commonly serve as the primary power source in vehicles including automobiles, trucks, motorcycles, locomotives, boats and aircraft.

This array of vehicles that utilizes the internal combustion engine illustrates the advantages of this engine type. Both the high powerto-weight ratio, and the overall reliability of ICEs, makes these engines ideal for mobile applications.

An internal combustion engine is able to create power and drive the designed engine parts using the energy created through combustion of fuel and oxidizers (typically air). The heat generated during combustion causes a rapid expansion of gases and thus pressure that can perform work on the mechanical components of the engine. This work is used to move pistons, turbine blades or other components within the engine.

Most ICEs are designed to be powered by either diesel or gasoline fuel. The mechanics of both engine designs are similar, but they employ a different ignition mechanism. The ignition process in gasoline engines typically relies on the combination of a lead-acid battery and an induction coil which provides a high-voltage electrical spark to ignite the air-fuel mixture within the engine cylinder. Ignition in a diesel engine is driven by the compression process that occurs in the engine. The heat and pressure created in this stage allows the fuel-air mixture to spontaneously ignite without the aid of a spark. The compression ratio[‡] is one the primary ways to characterize the difference in operating environments of the gasoline and diesel engines. Generally, gasoline engines operate with a compression ratio in the 8-12 range while the diesel engine operates over a higher range from 14-25.

The ability of diesel engines to operate at these higher compression ratios is the primary factor that dictates why diesel engines are typically more efficient than gasoline engines. In fact, diesel engines are less efficient than gasoline engines when operated at the same compression ratio. Modern gasoline engines are approximately 20-25% efficient on average while diesel engines are capable of efficiencies approaching 40%.[§§]

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TURBINE-BASED ENGINES

Turbines are critical components in energy conversion systems and are commonly found in automobiles, aircraft, refrigeration systems, and generators. Despite their wide application, turbines are primarily part of a larger machine. For example, a gas turbine may refer to an internal combustion engine with a turbine, ducts, compressor, combustor, heat-exchanger, fan and (in the case of one designed to produce electricity) an alternator. The most common turbinedriven systems are steam, gas, and/or jet turbines.

In general, a turbine-powered engine converts the energy of a moving stream to mechanical work. In the simplest systems, the stream flows across blades attached to the turbine (rotor) and the blades then are forced to rotate which generates energy that can be used to do work. Turbines are also valuable in energy conversion systems because they can operate at high speeds and are able to provide a high power density source.

FUEL CELLS

A fuel cell (FC) is a device that converts chemical energy from a fuel source to electrical energy via electrochemical reactions in the presence of a catalyst. An electric current is generated as electrons are freed in a half-cell reaction at one electrode, conducted through an external circuit from which electric power is drawn, and finally combined at the opposing electrode in the other half-cell reaction. In the meantime, ions are migrating across an electrolyte to participate in the reactions.

Much like batteries, with no moving parts fuel cells can silently and without vibration provide power. Since there is no mechanical wear, the expected life of a fuel cell is long. The primary difference between a fuel cell and a battery is the battery is a closed electrochemical system in which the reactants can be completely consumed and thus the output power eventually can be depleted. FCs have a continuous supply of reactants, and thus can operate without being recharged. While the fuel source can vary, the typical reactants are hydrogen and an oxidant, which is most often oxygen. While a hydrogen source must be provided, in most cases oxygen can be drawn from the air. The cellular aspect of these power devices is derived from their modular nature.

Fuel cells are typically organized according to the type of electrolyte used. The following sections briefly describe the main types of fuel cells.

Alkaline

Alkaline fuel cells (AFCs) contain an aqueous solution of potassium hydroxide (KOH), which serves as the electrolyte. Potassium hydroxide is used because it is the most conductive alkaline hydroxide.[46]

Hydroxide ions react with hydrogen as shown below to free electrons and produce water. This reaction occurs at the anode.

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

Hydroxide ions are produced at the cathode as oxygen is reacted with water and an input of electrons.

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

These types of FCs are very susceptible to contamination. A small amount of carbon dioxide in either of the reagent streams (i.e., hydrogen or oxygen) will result in carbonation of the potassium hydroxide. Ultimately, such a contamination would result in the formation of particulates which deposit in the porous electrode. Thus, AFCs require pure hydrogen and oxygen, and therefore are primarily used in space applications.

Molten Carbonate

Molten carbonate fuel cells (MCFCs) utilize a liquid solution of lithium, sodium, and/or potassium carbonates for the electrolytic medium. This is a hot corrosive liquid, and thus are primarily used for stationary applications.

The reaction at the anode involves a carbonate ion and hydrogen as shown below.

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$$

This produces water, carbon dioxide (CO2) and free electrons. The CO_2 must be recycled to the cathode side of the fuel cell where it is combined with oxygen and free electrons to form the carbonate ion as shown below.

$$½O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$$

Due to the high operating temperature of the fuel cell, natural gas can be used as the hydrogen source. Steam is also generated because of this high operating temperature, which can be harnessed for an auxiliary source of power.

Phosphoric Acid

Phosphoric acid fuel cells (PAFCs) utilize concentrated phosphoric acid as the electrolyte because it is a good ionic conductor at high temperatures. Since the electrolyte is a hot corrosive liquid, PAFCs are well-suited only for stationary applications.

The reaction at the anode involves separating the hydrogen into ions to produce free electrons as shown below.

$$H_2 \rightarrow 2H^+ + 2e^-$$

At the cathode, the hydrogen ions are combined with oxygen and free electrons to produce water as shown below.

$$½O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

The electrodes are made of carbon paper with a dispersion of platinum catalyst.

Polymer Electrolyte Membrane

Polymer electrolyte membrane (PEM) fuel cells (see Table 7), also known as proton exchange membrane fuel cells, rely on a specialized fluoropolymer membrane material that has sulfonic acid groups. The sulfonic groups facilitate ionic conduction under hydrated conditions. The operating temperature for PEMFCs is relatively cool (70°C).

The reactions on the anode and cathode side of the FC are the same as those shown for PAFCs.

Direct methanol fuel cells (DMFCs) are a subset of PEMFCs. These FCs utilize the same electrolyte material, but use a different fuel source (i.e., methanol) and thus a different catalyst (i.e., platinum/ruthenium alloy rather than carbon-platinum).

Solid Oxide

Solid oxide fuel cells (SOFCs) uses a solid ceramic material, yttria stabilized zirconia, for the electrolyte. These FCs must operate at high temperatures in order to readily conduct ions via the ceramic electrolyte. Due to the high operating temperatures, however,

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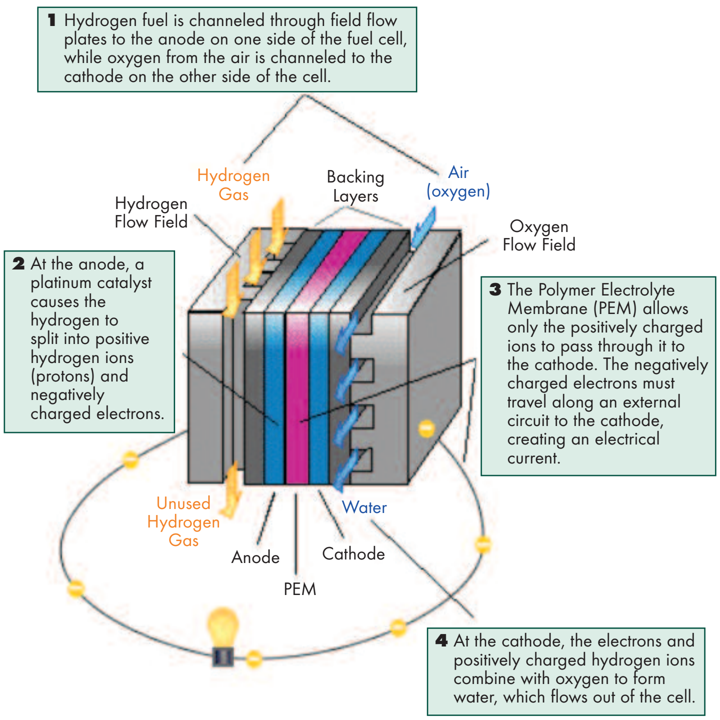

Figure 7. Diagram of a PEMFC.[47]

expensive catalysts are not required and hydrocarbon fuels can be used directly.

The Department of Energy Hydrogen Program has established a simple comparison of several fuel cell technologies. This comparison is provided in Table 7.

BI-FUEL ENGINES

Bi-Fuel/Dual Fuel Engines

Energy conversion processes have continued to evolve over time in order to meet the changing requirements of users. One such evolution in recent years has been the increase in development and implementation of engines that are capable of running, at least in part, on alternative fuels. These engines are operated using a mixture of gasoline or diesel and an alternative fuel (commonly compressed natural gas, CNG).[49]

Hybrid cars that use both electric and conventional combustion engines are becoming increasingly common as well. However, these hybrid vehicles are not the only alternative to internal combustion engines. Both bi-fuel and dual fuel engines are also available for automotive applications. One of most common examples of these engine types used in the US today can be found in cars that are designed to run on flex-fuel (typically: E85).[50]

The characteristics of bi-fuel and dual fuel engines are similar so the individual terms are sometimes used in conjunction with one another. There are two common mechanisms used in these engines to convert the fuel to energy for the engine. Engines of this type are characterized as follows:[51]

(1) The engine is designed to operate using a blended fuel mixture. Blends are commonly a mixture of petroleum based fuels (e.g., gasoline or diesel) and an alternative fuel (e.g., ethanol).

(2) The vehicle has two separate fuel systems where one is designed to provide an alternative fuel to the engine and the other is designed to store either gasoline or diesel. These engines can operate on either fuel type, but typically diesel-based engines are more common. A variety of manual and automatic systems for injecting the fuel into these engines can be used. These engines have typically been modified from their original specifications, but they can still operate on their original gasoline/diesel fuels.

The most common alternative fuels used in the first engine are CNG and ethanol. The US has seen an increasing market for flex fuel vehicles because the necessary modifications do not have a significant impact on the cost. The primary concern with engines of this type is the efficiency from burning ethanol. E85 blends can be 30% less efficient than regular gasoline blends. Thus, vehicle owners have to pay close attention to the cost of E85 in order to justify its use economically. These engines can operate on regular gasoline with little decrease in performance compared to an engine that has not been modified to run on blended fuels.

In the second case, natural gas is the primary fuel used, but these engines are also designed to function with diesel as the ignition source (functioning on heat of compression and not with a spark plug). These engines tend to operate on 100% diesel when they idle. Then, as the vehicle begins to approach full-load performance, natural gas is injected to replace the diesel fuel. The natural gas is injected in proportion to the increasing load and can reach 80% or more of the fuel. These design specifications make these engines valuable in circumstances where the use of natural gas is desired for environmental or economic reasons. Also, the natural gas supply does not have to be abundant since the engine can always be operated with the factory designed fuel.

BATTERIES

The namesake of the common electrical battery has an inherently military origin. The term battery, used to describe a unit of artillery working together, was used by Benjamin Franklin to describe a set of Leyden jars, which are devices that store electrical charge and were the precursor to the capacitor.[52]

The fundamental unit of a battery is an electrochemical cell (also known as a galvanic or voltaic cell), which converts chemical energy to electrical energy through chemical reactions that cause electrons to move from one electrode to another. A galvanic cell has two electrodes, an anode (negative terminal) and a cathode (positive terminal) which are connected through an electrically

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Table 7. **Comparison of fuel cell technologies.[48]**

Fuel Cell Type	Common Electrolyte	Operating Temperature, °C	System Output, kW	Electrical Efficiency, %	Combined Heat and Power (CHP) Efficiency, %	Applications	Advantages
Polymer Electrolyte Membrane	Solid organic polymer poly-perfluorosulfonic acid	50-100	<1-250	53-58 (transportation) 25-35 (stationary)	70-90 (low grade waste heat)	• Backup power • Portable power • Small distributed generation • Transportation • Specialty Vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature Quick start-up
Alkaline	Aqueous solution of potassium hydroxide soaked in a matrix	90-100	10-100	60	>80 (low grade waste heat)	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to higher performance • Can use a variety of catalysts
Phosphoric Acid	Liquid phosphoric acid soaked in a matrix	150-200	50-1000 (250kW module typical)	>40	>85	• Distributed generation	• Higher overall efficiency with CHP • Increased tolerance to impurities in hydrogen
Molten Carbonate	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700	50-1000 (250kW module typical)	45-47	>80	• Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP
Solid Oxide	Yttria stabilized zirconia	600-1000	<1-3000	35-43	<90	• Auxiliary power • Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces electrolyte management problems • Suitable for CHP • Hybrid/GT cycle

conductive medium, or electrolyte, and an electrically conductive path. When the electrodes are electrically connected, electrons are generated via an oxidation-reduction reaction and flow across the conductive pathway from the anode to the cathode, while ions migrate through the electrolyte. Batteries can store chemical energy when the conductive path is not connected.

The increasing number of electronic devices being used by deployed forces puts a greater emphasis on developing longer lasting, lightweight batteries. Many efforts are focused on more efficient batteries which have a higher energy density. Energy density refers to the ratio of power a battery can supply relative to its own weight. There are many variations in battery design and deciding on the proper battery for a given application depends on the nature of use and the environment in which the battery will be operated. Discharge temperature, rate of discharge, ventilation, mobility, weight, and repeatable use, are among the main design considerations for batteries. Batteries can essentially be placed in one of two categories: primary and secondary.

Primary Batteries

Primary batteries, also known as disposable batteries, generate power with an irreversible reaction, and thus it is not practical to recharge them. Once the initial reactants have been depleted, the battery is no longer useful for power applications, however many still have some value and can be recycled.

Alkaline Batteries

Alkaline batteries are one common type of disposable battery and have remained popular because they typically offer higher power densities than rechargeable batteries. Their high power capacity is due to their high electrochemical efficiency and makes them favorable for long duration discharge.[53] However, they are not well suited for all applications and provide poor performance under high drain applications over 75 ohms.

Alkaline batteries typically have zinc (Zn) and manganese dioxide (MnO2) electrodes and are named for their electrolyte, which is an alkaline compound (potassium hydroxide). Zinc and manganese dioxide react through the potassium hydroxide electrolyte to form zinc oxide (ZnO) and a manganese oxide (Mn_2O_3).[54]

Zinc-Carbon Batteries

Based on the Leclanche cell, zinc-carbon batteries offer the cheapest primary battery design but weak performance.[55] They are comprised of a zinc anode, which also serves as the battery case; a carbon rod that serves as the cathode and is surrounded by manganese dioxide and carbon black; and a paste of

ammonium chloride and zinc chloride, which serves as the electrolyte.[56] They are considered to have a good shelf life.

Mercuric-Oxide Batteries

Mercury (Hg) has been used as an additive in batteries for well more than a hundred years, and it is still used today despite the known environmental effects. The use of metallic mercury as an additive by US manufacturers has diminished dramatically over the past several decades primarily due to federal law, but other mercury-based compounds are still used in regulated fashion. Alkaline button cell batteries are permitted to contain up to 25 mg of Hg. Other types of button cell batteries, such as zinc-air and silver oxide, contain small amounts of mercury (i.e., average content less than 25 mg).[57]

In mercuric-oxide batteries, the cathode is zinc, the electrolyte is potassium hydroxide and the mercuric oxide (HgO) serves as the anode. The Mercury-Containing Battery Management Act of 1996 prohibits the sale of the button cell form of mercuric-oxide batteries, and the larger variety of these batteries are regulated and restricted to military and medical use.[57] These batteries are carefully managed and recycled.

Zinc-Air Batteries

Atmospheric oxygen can be used as the oxidizing agent for electrochemical cells. The use of an abundant and widely available resource for the oxidizing agent or cathode reactant allows zinc-air batteries greater zinc anode capacity and therefore other attractive performance properties. For example, zinc-air batteries have five times the anode capacity compared to conventional zinc-anode batteries.lviii Zinc-air batteries use zinc for the anode, air as the cathode reactant and potassium hydroxide as the electrolyte. Advantages of zinc-air batteries include high energy density, constant discharge, good shelf-life, and low operating cost.

Secondary Batteries

The ability to recharge a battery or reverse the chemical reaction in the cell by supplying electrical energy to the cell is the defining characteristic of secondary batteries. Rechargeable batteries do not have an infinite lifecycle and ultimately will begin to lose their ability to hold a charge for a number of reasons such as dissipation of the active materials, loss of electrolyte and internal corrosion.

Lead Acid Batteries

The lead-acid battery is a rechargeable wet cell battery suitable for applications where weight is not as critical of a factor. Their construction includes a liquid filled container which must remain upright and well ventilated to release volatile hydrogen gas: a product of overcharging. Lead plates serve as the electrodes, and the electrolyte is a sulfuric acid (H_2SO_4) solution.

Although lead-acid batteries possess a poor energy-to-weight ratio they can provide a high power-to-weight ratio and are relatively cheap to manufacture, thus making them the optimal choice for many applications. Even as the oldest form of rechargeable battery, they are still the most popular choice for automobiles and other vehicles that need to provide high current to a device such as an electric starter.

Lithium-Ion Batteries

With a higher energy-to-volume ratio, sealed dry cell batteries are well suited for portable power applications. There are several different material combinations which can be used for the chemical reaction in dry cell batteries. Nickel-cadmium (NiCd) and nickel metal hydride (NiMH) are of the most well known battery types with lithium-ion (Li-ion) currently being the most popular and fastest growing.

Li-ion batteries contain a lithium ion which travels between the anode and cathode when discharging. When electricity is added to the cell the ion moves in the reverse direction, from cathode to anode, thereby charging the battery. The electrodes of a lithium-ion battery are made of lightweight lithium and carbon. Lithium is a highly reactive element that stores a large amount of energy in its atomic bonds. Thus, a high energy density is obtainable with Li-ion batteries. The voltage, capacity, life, and safety of a lithium ion battery can change dramatically depending on the choice of material used for the anode, cathode, and electrolyte. This design flexibility is favorable but can also make them dangerous if they are not implemented correctly. As higher charge densities are achieved in Li-ion batteries safety concerns and related manufacturing costs increase. Li-ion batteries are very popular choice for portable electronics because they have an excellent energy-to-weight ratio, do not maintain memory, and have a slow self-discharge when not in use.

Nickel-Cadmium Batteries

NiCd batteries are capable of producing large surge currents which is ideal for devices which require a large current such as power tools. The use of cadmium, a toxic heavy metal, however, makes them an environmental hazard and requires special disposal. NiCd batteries primarily compete with alkaline batteries. While they cannot match the charge capacity of alkaline batteries they have the advantage of being rechargeable.

Nickel Metal Hydride Batteries

NiMH battery uses a hydrogen-absorbing alloy for the negative electrode instead of cadmium. They can have up to three times the energy density of an similarly sized NiCd battery and have been a popular battery choice for hybrid vehicles. In comparison to the Li-ion battery NiMH batteries have a lower charge density and therefore offer inferior performance in many portable electronic devices. Additionally, their high self discharge rate makes them impractical for many slow discharge devices such as clocks or remotes. They are better suited for high-rate discharge than alkaline batteries due to their lower internal resistance. For instance, in digital cameras, NIMH batteries can sustain a con-

stant voltage at high current discharge for a longer period of time and of course maintain the added benefit of being rechargeable. NiMH batteries tend to have the quickest rate of self discharge and are a poor option for long term energy storage.

NOTES & REFERENCES

* Aliphatic compounds are organic molecules comprised of hydrogen and carbon atoms bonded together in the form of a straight chain.

† Paraffins, also known as alkanes, are saturated hydrocarbons, in which carbon atoms are singly bonded to other carbon atoms and hydrogen atoms.

‡ Naphthenes, also known as cycloalkanes, are saturated hydrocarbons containing at least one ring of carbon atoms.

§ Aromatics are hydrocarbons that have hexagonal ring structures with alternating single and double bonds between the carbon atoms.

** Olefins, also known as alkenes, are unsaturated hydrocarbons containing at least one double carbon-carbon bond.

†† Flash point is the minimum temperature needed for the vapor above a volatile liquid to form an ignitable mixture with air. At the flash point there is just enough vapor in the air above the liquid to make the mixture flammable and able to release its energy through combustion.

‡‡ A secondary energy source is energy derived from another energy source. Gasoline and other refined fuels can be categorized as a secondary energy source.

§§ Compression Ratio: A value that represents the ratio of the volume of a combustion chamber from its largest capacity to its smallest. It is one of the fundamental specifications given for modern combustion engines.

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